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Control of the e-p Instability at the Proton Storage Ring

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The strong transverse instability long observed at the Los Alamos Neutron Science Center (LANSCE) Proton Storage Ring (PSR) has been a limiting factor on peak intensity and is widely considered a major technical risk to the next generation of high-intensity proton rings. It has been the subject of much recent research that has led to a deeper understanding of its mechanism and several methods of control. The evidence is now compelling that this is a two-stream, electron-proton (e-p) instability caused by coupled oscillations of a low-energy electron cloud with the intense PSR beam. Experiments at PSR and various simulations have shown that a form of beam-induced multipacting (electron avalanche caused by multiple collisions with the PSR wall) on the trailing edge of the long PSR pulse generates a strong electron cloud. Furthermore, sufficient electrons survive the passage of beam-free gaps to cause an e-p instability with the characteristics observed at PSR.

A number of potential cures have been tested at PSR and found to be useful in significantly raising the instability threshold. Various measures to increase the spread of the betatron-wave frequency (and thereby increasing Landau damping) have been effective and are now implemented in PSR as part of the Short-Pulse Spallation Source (SPSS) Enhancement Project. Control of the instability by suppressing the generation of electron clouds has also been studied experimentally at PSR. As a result of these studies, global conditioning, or beam scrubbing, of the vacuum-chamber surfaces in the PSR has raised the instability threshold. (Beam scrubbing refers to the bombardment of the chamber surfaces with an intense electron cloud created by beam-induced multipacting.) Other methods of electron suppression (i.e., TiN coatings, use of weak magnetic solenoid fields) have been effective in reducing the electrons in short test sections but have not been tried over a large fraction of the ring circumferences. The measures that have been implemented at PSR have been sufficient to raise the instability threshold to 10 μC/pulse (6 x 10^{13} proton/pulse).

Instability Characteristics

Measurement of the instability threshold is typically done by accumulating a given number of protons and storing them for 400 to 500 μs after the end of accumulation. The radio-frequency (rf) buncher voltage is lowered until (1) the high-frequency, unstable motion appears on the vertical-difference signal of a beam-position monitor (BPM) near the end of the beam storage, and (2) a significant amount of beam is lost, as shown in the oscilloscope traces of Fig. 1. The growth time for the unstable motion is in the 50- to 100-μs range. Compelling evidence for e-p instability includes the observation that (1) the frequency content of the unstable motion is predominately at the bounce frequency of electrons captured in the potential well of the beam, and (2) the center frequency at threshold varied with the square root of the beam intensity as predicted for the e-p instability.

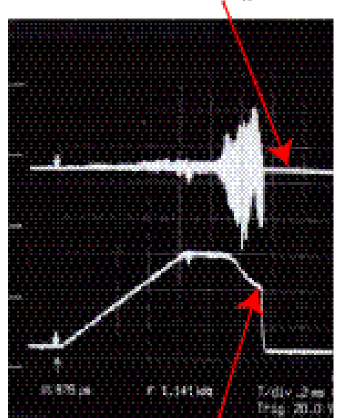

Fig. 1. Oscilloscope traces of diagnostic signals from the e-p instability at PSR.

Control by Landau Damping

Early models of the e-p instability predicted that Landau damping would be an important process because an increase in the spread of betatron-wave frequencies (caused by the spread of the momentum of the particle beam) results in more damping of the instability. The damping was observed in the strong linear dependence of the instability threshold on rf-buncher voltage (which increased the proton-beam momentum spread) shown in the curve labeled *historical data* in Fig. 2. An upgrade of the rf buncher to raise the maximum reliable voltage from 12 kV to 18 kV was part of the SPSS Enhancement Project and was important for control of the instability at higher-peak intensities. Other methods of increasing the betatron frequency spread to create additional Landau damping include the use of higher-order multipole fields (i.e., sextupole and octupole magnets), coupling of the betatron oscillations with a skew-quadrupole magnet (i.e., magnet rotated 45° about the beam axis), and inductive inserts. The inductive inserts are a passive means of compensating for the effects of longitudinal-space-charge fields and are equivalent to adding additional rf voltage, which further increases the momentum spread and damping of the instability. In addition, the inductors are effective in keeping beam from leaking into the gap between bunch passages under the influence of longitudinal-space-charge forces. A small amount of beam in the gap can trap additional electrons, which will contribute to the instability.

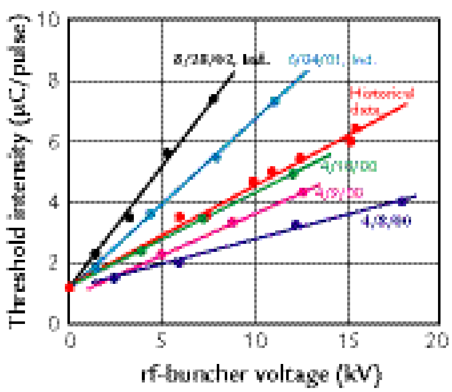

Fig. 2. e-p instability threshold-intensity curves taken at various dates during the 2000 to 2002 beam operations. The data for 2001 and 2002 also include the effect of inductive inserts.

Suppressing the Generation of the Electron Cloud

Our studies in 2002 focused on testing measures to reduce the electron cloud and the hypothesis that reduction of the electron-cloud generation will raise the instability threshold. To this end, two additional sections were coated with TiN, which is effective in reducing the prompt multipactor electrons. The new tests with the additional TiN coatings showed an immediate factor-of-10 reduction of electrons in section 9 of the PSR. Although there was no initial reduction of the electron cloud in section 4, it did improve over time during beam operations. After 10 weeks of production-beam operations at 100 to 110 µA, the prompt-electron signal was reduced by about a factor of 20, and the electrons remaining in the pipe at the end of the gap were down a factor of 5 — another indication of the benefit of surface conditioning by the beam.

Electron bombardment of vacuum-chamber surfaces has been shown to reduce the secondary emission yield in bench experiments at other laboratories. We therefore expected beam scrubbing to reduce the electron-cloud generation and the resulting e-p instability over time. Fig. 2 shows the instability-threshold curve that we measured at PSR at various times during the 2000 to 2002 beam operations. These data show considerable improvement in the instability threshold intensity over time. A systematic reduction in the prompt-electron-cloud signal (as measured by electron detectors in the PSR) by about a factor of 10 was also measured during the 2002 run cycle.

Conclusion

As a result of extensive beam-physics research, the strong transverse instability at PSR is reasonably well understood in terms of a two-stream, e-p instability caused by the coupled oscillations of a low-energy electron cloud with the intense proton beam in PSR. The intense electron cloud is produced from beam-induced multipacting on the trailing edge of the long beam pulse and from the high reflectivity of low-energy electrons. The high reflectivity allows significant numbers to survive the 80- to 100-ns gap between bunch passages. Reduction of the electron cloud by beam scrubbing over time and by using several measures to enhance Landau damping have permitted us to stably store peak proton intensities up to 10 µC/pulse (6×10^{13} protons/pulse), which is a factor-of-2 improvement compared to the value achieved before these improvements.

References

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